Introduction to Cosmic Rays*

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Abstract. Energetic particles, traditionally called *Cosmic Rays*, were discovered nearly a hundred years ago, and their origin is still uncertain. Their main constituents are the normal nuclei as in the standard cosmic abundances of matter, with some enhancements for the heavier elements; there are also electrons, positrons and anti-protons. Today we also have information on isotopic abundances, which show some anomalies, as compared with the interstellar medium. And there is antimatter, but no anti-nuclei. The known spectrum extends over energies from a few hundred MeV to 300 EeV ($= 3 \times 10^{20}$ eV), and shows few clear spectral signatures: There is a small spectral break near 5×10^{15} eV, commonly referred to as the *knee*, where the spectrum turns down; there is another spectral break near 3×10^{18} eV, usually called the *ankle*, where the spectrum turns up again. Up to the ankle the cosmic rays are usually interpreted as originating from supernova explosions, i.e. those cosmic ray particles are thought to be Galactic in origin; however, the details are not clear. We do not know what the origin of the knee is, and what physical processes can give rise to particle energies in the energy range from the knee to the ankle. The particles beyond the ankle have to be extragalactic, it is usually assumed, because the Larmor radii in the Galactic magnetic field are too large; this argument could be overcome if those particles were very heavy nuclei as Fe, an idea which appears to be inconsistent, however, with the airshower data immediately above the energy of the ankle. Due to interaction with the cosmic microwave background (CMB), a relic of the Big Bang, there is a strong cut-off expected near 50 EeV ($=5 \times 10^{19}$ eV), which is, however, not seen; this expected cutoff is called the GZK-cutoff after its discoverers, Greisen, Zatsepin and Kuzmin. The spectral index α is near 2.7 below the knee, near 3.1 above the knee, and again near 2.7 above the ankle, where this refers to a differential spectrum of the form $E^{-\alpha}$ in numbers. The high energy cosmic rays beyond the GZK-cutoff are the challenge to interpret. We will describe the various approaches to understand the origin and physics of cosmic rays.

1 Introduction and History

Cosmic Rays were discovered by Hess [1] and Kohlhörster [2] in the beginning of the twentieth century through their ionizing effect on airtight vessels of glas enclosing two electrodes with a high voltage between them. This ionizing effect increased with altitude during balloon flights, and therefore the effect must

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come from outside the Earth. So the term *Cosmic Rays* was coined. The Earth's magnetic field acts on energetic particles according to their charge, they are differently affected coming from East and West, and so their charge was detected, proving once and for all that they are charged particles. At the energies near 10^{18} eV there is observational evidence, that a small fraction of the particles are neutral, and in fact neutrons; these events correlate on the sky with the regions of highest expected cosmic ray interactions, the Cygnus region and the Galactic center region. From around 1960 onwards particles were detected at or above 10^{20} eV, with today about two dozen such events known. It took almost forty years for the community to be convinced that these energies are real, and this success is due to the combination of air fluorescence data with ground-based observations of secondary electrons/positrons and muons, as well as Čerenkov light; the Fly's Eye [3], Haverah Park [4] and AGASA [5] arrays are those with the most extensive discussion of their data out and published; other arrays have also contributed a great deal, like Yakutsk [8], Volcano Ranch [9] and SUGAR [10]. Already in the fifties it was noted that protons with energies above 3×10^{18} eV have Larmor radii in the Galactic magnetic field which are too large to be contained, and so such particles must come from outside [11]. After the CMB was discovered, in the early 1960s, it was noted only a little later by Greisen [12], and Zatsepin and Kuzmin [13], in two papers, that near and above an energy of 5×10^{19} eV (called the GZK-cutoff) the interaction with the CMB would lead to strong losses, if these particles were protons, as is now believed on the basis of detailed airshower data. In such an interaction, protons see the photon as having an energy of above the pion mass, and so pions can be produced in the reference frame of the collision, leading to about a 20 % energy loss of the proton about every $\simeq 6\,$Mpc in the observer frame. Therefore for an assumed cosmologically homogeneous distribution of sources for protons at extreme energies, a spectrum at Earth is predicted which shows a strong cutoff at 5×10^{19} eV, the GZK-cutoff. This cutoff is not seen, leading to many speculations as to what the nature of the particles beyond the GZK-energy, and their origin might be.

Cosmic rays are measured with balloon flights, satellites, now with instruments such as AMS [14] on the Space Shuttle, and soon also with instruments on the International Space Station [15], and with Ground Arrays. The instrument chosen depends strongly on what is being looked for, and the energy of the primary particle. One of the most successful campaigns has been with balloon flights in Antarctica, where the balloon can float at about 40 km altitude and circumnavigate the South Pole once, and possibly even several times during one Antarctic summer. For very high precision measurements very large instruments on the Space Shuttle or soon the International Space Station have been or will be used, such as for the search for antimatter. The presently developed new experiments such as the fluorescence detector array HiRes [17] and the hybrid array Auger [18], are expected to contribute decisively to the next generation of data sets for the highest energies.

Critical measurements are today the exact spectrum of the most common elements, Hydrogen and Helium, the energy dependence of the fraction of anti-

particles (anti-protons and positrons), isotopic ratios of elements such as Neon and Iron, the ratio of spallation products such as Boron to the primary nuclei such as Carbon as a function of energy, the chemical composition near and beyond the knee, at about 5×10^{15} eV, and the spectrum and nature of the particles beyond the ankle, at 3×10^{18} eV, with special emphasis on the particles beyond the expected GZK-cutoff, at $\simeq 5 \times 10^{19}$ eV. The detection of anti-nuclei would constitute a rather extreme challenge. One of the most decisive points is the quest for the highest energy events and the high energy cutoff in the spectrum. This is also the main topic of the present volume. The data situation and experimental issues involved at the highest energies have been reviewed in Refs. [19,20].

Relevant reviews and important original papers have been published over many years, e.g., [21,22,23,24,25,26,27,28].

2 Physical Concepts

2.1 Cosmic Ray Spectrum and Isotropy

The number of particles at a certain energy E within a certain small energy interval dE is called the spectrum. Cosmic rays have usually a powerlaw spectrum, which is referred to as a non-thermal behaviour, since non-thermal processes are thought to be producing such spectra. Flux is usually expressed as the number of particles, coming in per area, per second, per solid angle in steradians (all sky is $4\ \pi$), and per energy interval. Cosmic rays have a spectrum near $E^{-2.7}$ up the the knee, at about 5×10^{15} eV, and then about $E^{-3.1}$ beyond, up the ankle, at about 3×10^{18} eV, beyond which the spectrum becomes hard to quantify, but can very approximately again be described by $E^{-2.7}$. There is no other strong feature in the spectrum, especially no cutoff at the upper end. There is some limited evidence from the newest experiments (AGASA [5] and HiRes [17,29]) for another feature, at about 3×10^{17} eV, called *the second knee*, where the spectrum appears to dip. Both the first and the second knee may be at an energy which is proportional to charge [30], i.e. at a constant Larmor radius, and therefore may imply a range in energies per particle. Figure 1 shows the overall cosmic ray spectrum.

There is no anisotropy except for a weak hint near 10^{18} eV [31,32,33], and the suggestive signal for pairing at energies near and beyond the GZK-cutoff [34].

2.2 Fermi Acceleration

In a compressing system the particles gain energy; the walls can be magnetic irregularities which reflect charged particles through magnetic resonance between the gyromotion and waves in the ionized magnetic gas, the plasma. Such magnetic irregularities usually exist everywhere in a plasma that gets stirred by, e.g., stellar ultraviolet radiation and their ionization fronts, by stellar winds, supernova explosions, and by the energetic particles moving through. Considering

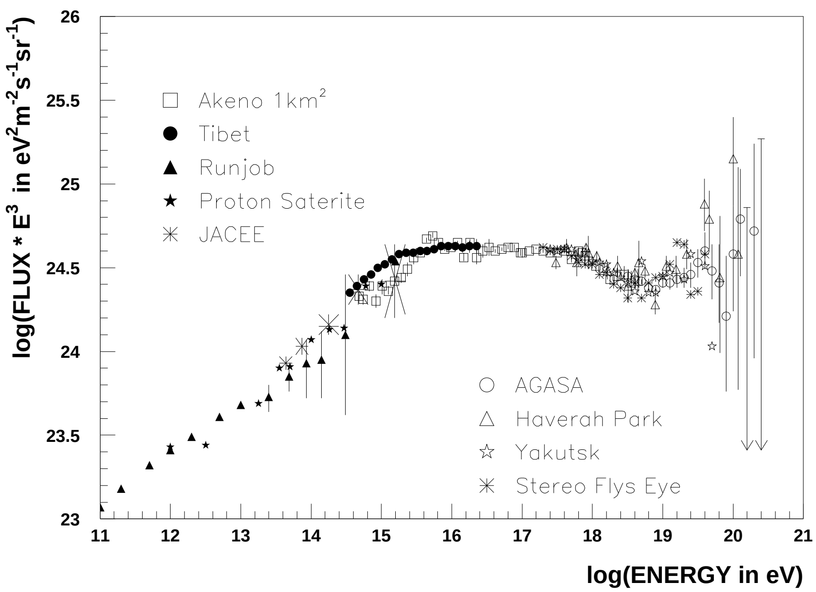

Fig. 1. The CR all-particle spectrum observed by different experiments above 10^{11} eV (from Ref. [20]). The differential flux in units of events per area, time, energy, and solid angle was multiplied with E^3 to project out the steeply falling character. The "knee" can be seen at $E \simeq 4 \times 10^{15}$ eV, the "second knee" at $\simeq 3 \times 10^{17}$ eV, and the "ankle" at $E \simeq 5 \times 10^{18}$ eV

now the two sides of a shock, one realizes that this is a permanently compressing system for charged particles which move much faster than the flow in the shock frame. Therefore particles gain energy, going back and forth. In one cycle they normally gain a fraction of U_{sh}/c in momentum (adopting relativistic particles here), and the population loses a fraction of also U_{sh}/c. Here U_{sh} is the shock velocity. For the original articles by E. Fermi see Ref. [21], Ref. [35] for a recent review, and see also the contribution by G. Pelletier in this volume.

The density jump r in an adiabatic shockfront is given by the adiabatic index of the gas γ and the upstream Mach number of the shock M_1

$$r = \frac{\gamma + 1}{\gamma - 1 + 2/M_1^2} \tag{1}$$

The general expression for the spectral index of the particle momentum distribution p^{-a} is

$$a = \frac{3r}{r-1} \tag{2}$$

This is in three-dimensional phase space; the energy distribution then is given by E^{2-a}, for relativistic particles. This means, for instance, that for a very large Machnumber and the standard case of $\gamma = 5/3$ the density jump is 4, and the spectral index is $a - 2 = 2$. For $\gamma = 4/3$, as would be the case in a gas with a relativistic equation of state (like a radiation dominated gas) the density jump is 7, and the spectral energy index of the particles is $a - 2 = 3/2$. The time scale for acceleration is given in, e.g., [36,37].

In a relativistic shock wave the derivation no longer holds so simply for the spectrum; however, it is worth noting that the density jump can go to infinity both in the case of a relativistic shockwave as in the case of a strong cooling shock. Then the spectral index in energy approaches $a - 2 = 1$. However, detailed Monte-Carlo simulations for relativistic shocks, taking into account the highly anisotropic nature of the scattering as well as the particle distribution, again find a spectrum near 2 [38]. For more details on Fermi acceleration see also the contribution by G. Pelletier in this volume.

2.3 Spallation

Spallation is the destruction of atomic nuclei in a collision with another energetic particle, such as another nucleus, commonly a proton [39,40,41]. In this destruction many pieces of debris can be formed, with one common result the stripping of just one proton or neutron, and another common result a distribution of lighter nuclei. Since the proton number determines the chemical element, these debris are usually other nuclei, such as Boron, from the destruction of a Carbon nucleus. It is an interesting question, whether these collisions lead to a new state of matter, the quark-gluon plasma; the Relativistic Heavy Ion Collider (RHIC) experiment [42] performed at Brookhaven collides heavy nuclei with each other, in order to find evidence for this new state. Both in our upper atmosphere and out in the Galaxy such collisions happen all the time, at very much higher energy than possible in the laboratory, and may well be visible in the data. Conversely, the existing data could be used perhaps to derive limits on what happens when a quark-gluon plasma is formed.

As a curiosity we mention that collisions of energetic cosmic rays with each other and with large objects such as the moon have been used to constrain the risk that high energy collisons in terrestrial accelerators could produce particles or new vacuum states that would trigger a phase transition to a lower energy state such as strange quark matter which would destroy the Earth [43]. This risk can be determined by calculating how much more often such processes occurred naturally involving cosmic rays since the birth of our Universe.

2.4 Chemical Abundances

The chemical abundances in cosmic rays are rather similar to first approximation to those in the interstellar medium [44]. We consider them in the following framework: We plot the number of particles per energy interval as a function of energy per particle, and normalize at 1 TeV energy per particle, so as to be free

of any solar modulation effect [45]. And we refer to Silicon for the comparison, so by definition the abundance for Silicon is adopted to be equal for cosmic rays and for the so-called cosmic abundances in the interstellar medium. In this well defined frame-work we then note the following differences:

- The abundance of Hydrogen is very much less for cosmic rays, as is the ratio of Hydrogen to Helium.
- The abundances of the elements Lithum, Beryllium and Boron are very much larger in cosmic rays than in the interstellar medium, by several powers of ten.
- The abundances of the sub-Iron elements are also larger than relative to Iron for cosmic rays.
- The abundances of odd-Z elements are larger.
- And, finally, those elements with a low first ionization potential are systematically more abundant.

These tendencies can be seen in Fig. 2 which compares solar System abundances with abundances in cosmic rays at 1 TeV.

In addition, the isotopic ratios among a given element are sometimes very similar to those in the interstellar medium, and for other cases, very different, indicating rather specific source contributors.

In all versions of theories it is acknowledged that spallation of abundant elements plays a major role, especially for the light elements, where spallation and subsequent ionization loss can even explain the abundances of the light elements in the interstellar medium. This is an especially interesting test using the light element abundances in stars formed in the young years of our Galaxy [46].

2.5 Cosmic Ray Airshower

When a primary particle at high energy, either a photon, or a nucleus, comes into the upper atmosphere, the sequence of interactions and cascades form an airshower. This airshower can be dominated by Čerenkov light, a bluish light, produced when particles travel at a speed higher than the speed of light c divided by the local index of refraction (which is $4/3$ in water, for instance, and about 1.0003 in air). Observing this bluish light allows observations of high GeV to TeV photon sources in the sky. For particles, such as protons, or atomic nuclei, the resulting airshower is dominated by air fluorescence, when normal emission lines of air molecules are excited, and by a pancake of secondary electrons and positrons as well as muons. Most modern observations of very high energy cosmic rays are done either by observing the air fluorescence, (arrays such as Flys's Eye [3], HiRes [17], or Auger [18]), or by observing the secondary electrons and positrons (in arrays such as Haverah Park [4], AGASA [5], Yakutsk [8], or also Auger [18]). In the further future such observations may be possible from space, by observing the air fluorescence, or also the reflected Čerenkov light, from either the International Space Station, or from dedicated satellites. Fly's Eye was and HiRes is in Utah, USA, Auger is in Argentina, AGASA is in Japan,

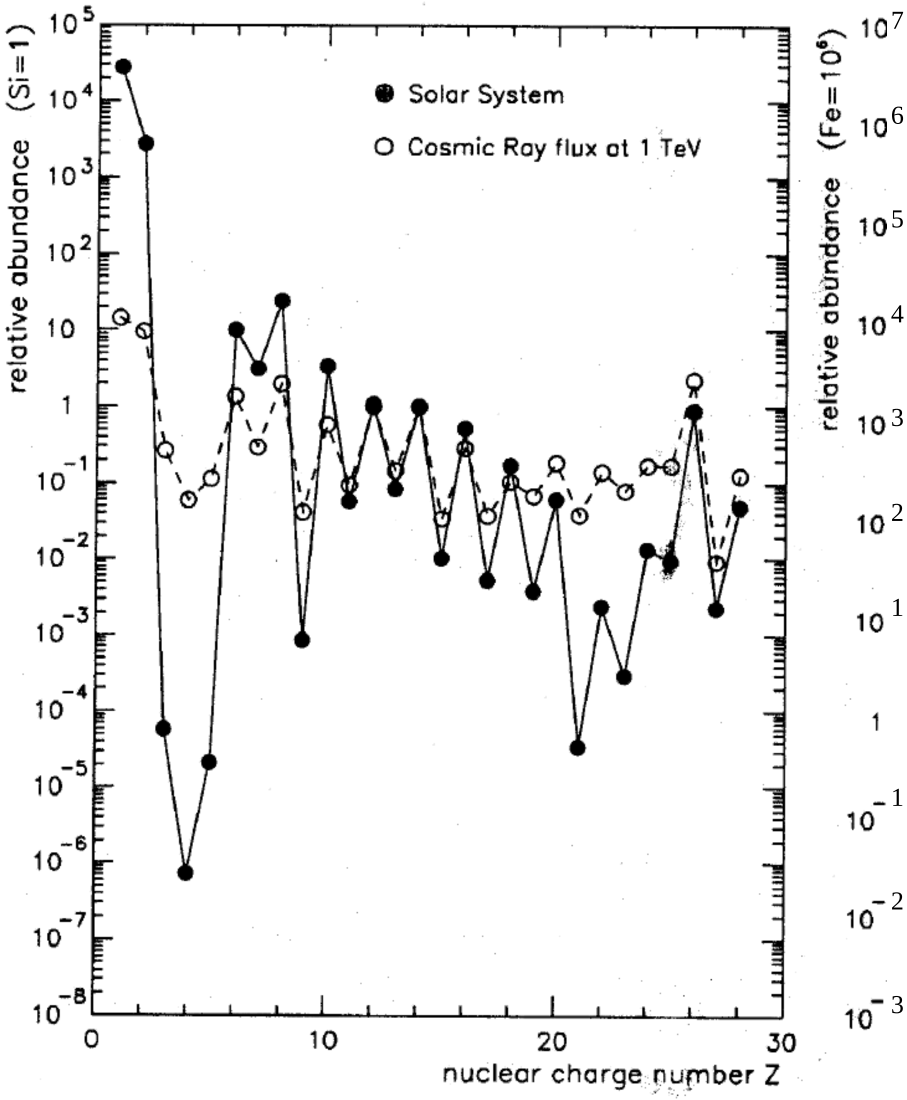

Fig. 2. The chemical composition of cosmic rays relative to Silicon and iron at 1 TeV, and in the solar System, as a function of nuclear charge Z, from Ref. [45]

Yakutsk is in Russia, and Haverah Park was in the United Kingdom. Future planned experiments are EUSO [47] on the space station, built by the ESA, and, even later, a satellite mission, OWL [49], discussed by NASA. For reviews of experimental techniques to detect giant airshowers see Refs. [19,20].

2.6 Cosmic Ray GZK-Cutoff

The interactions with the CMB should produce a strong cutoff in the observed spectrum, at 5×10^{19} eV, called the GZK-cutoff [12,13,50]. This is expected provided that a) these particles are protons (or neutrons), and b) the source distribution is homogeneous in the universe. This cutoff is not seen; in fact, no cutoff is seen at any energy, up to the limit of data, at $\simeq 3 \times 10^{20}$ eV, or 300 EeV. This is one of the most serious problems facing cosmic ray physics today. Assuming a source distribution just as the observed galaxy distribution alleviates the problem, but does not solve it [51,52] (see also the contribution by G. Medina Tanco in this volume).

2.7 Black Holes

It is now believed that almost all galaxies have a massive black hole at their center, with masses sometimes ranging up 10^{10} solar masses, but usually much less. There are also stellar mass black holes, but their number is not well known, probably many thousands in each galaxy. The growth of these black holes has almost certainly put an enormous amount of energy into the universe, possibly commensurate with other forms of baryonic energy. The ratio of the masses of the black holes and the stellar spheroidal component of older stars has a narrow distribution which is limited from above by about 1:300. There is a near perfect correlation between black hole mass and the velocity dispersion of the inner stars of the central cusp around the black hole [53,54,55,56]. These black holes can be expected to interact strongly with their environment, both in stars and in gas [57].

2.8 Our Galaxy

Our galaxy is a flat distribution of stars and gas, mixed with interstellar dust, and embedded in a spheroidal distribution of old stars. The age of this system is about 15 billion years; its size is about 30 kpc across, and its inner region is about 6 kpc across. At its very center there is a black hole with 2.6×10^6 solar masses [58]. The gravitational field is dominated in the outer parts of the Galaxy by an unknown component, called dark matter, which we deduce only through its gravitational force. In the innermost part of the galaxy normal matter dominates. The mass ratio of dark matter to stars to interstellar matter in our Galaxy is about 100:10:1. Averaged over the nearby universe these ratios are shifted in favor of gas, with gas dominating over stars probably, but with dark matter still dominating over stars and gas by a large factor. The universal ratios

of baryonic matter, dark matter and the Λ-term have been tightly constrained by the observation of the first three waves in the fluctuation spectrum of the CMB by the balloon experiments BOOMERanG [59], MAXIMA [60], and the ground detector DASI [61], as well as by measurements of the relation between apparent magnitude and redshift of certain type Ia supernovae which serve as "standard candles" of known absolute luminosity [62]. All experiments agree rather well in these conclusions [63]. In very small galaxies the dark matter component dominates over baryonic matter even at the center [64,65].

2.9 Interstellar Matter

The gas in between the stars in our Galaxy is composed of very hot gas (order 4×10^6 K), various stages of cooler gas, down to about 20 K, dust, cosmic rays, and magnetic fields [66,67,68,69]. All three components, gas, cosmic rays, and magnetic fields, have approximately the same energy density, which happens to be also close to the energy density of the CMB, about 1 eV per cm^3. The average density of the neutral hydrogen gas, of temperature a few 10^3 K, is about 1 particle per cm^3, in a disk of thickness about 100 pc ($= 3 \times 10^{20}$ cm). The very hot gas extends much farther from the symmetry plane, about 2 kpc on either side.

2.10 Magnetic Fields

Magnetic fields are ubiquitous in the Universe [70,71,72] (see also the contribution by G. Medina Tanco in this volume). In our Galaxy they have a total strength of about 6 - 7 microGauss (μG) in the solar neighborhood, and about 10 μG further in, at around 3 kpc from the center. The magnetic field is partially irregular, partially regular, with roughly 1/2 to 2/3 of it in a circular ring-like pattern; other galaxies demonstrate that the underlying symmetry is dominated by a spiral structure with the overall magnetic field pointing inwards along the spiral. One level down in scale, the fine structure is then of occasional reversals, but still mostly parallel to a circle around the center. At the small scales, less than the thickness of the hot disk, it appears that the magnetic field can be described as a Kolmogorov turbulence spectrum [73], all the way down to dissipation scales.

The origin of the magnetic field is not understood [74,75,76]. Comparing our Galaxy with others, in the starburst phase, and also at high redshift makes it obvious that the magnetic field is regenerated at time scales which are less or at most equal to the rotation time scale, with circumstantial evidence suggesting that this happens at a few times 10^7 years. Interestingly, this is the same time scale at which convection losses transport energy from the disk of the Galaxy, and on which cosmic ray energy is lost. We do not have a real understanding of what drives the energy balance of the interstellar medium.

2.11 Transport of Cosmic Rays

From the ratio of radioactive isotopes resulting from spallation to stable isotopes we can deduce the time of transport of cosmic rays near 1 GeV: It is about 3×10^7 years. This is very similar to the sound crossing time scale across the hot thick disk of the interstellar medium, and also to the Alfvénic time scale across the same thick disk. It is unlikely that these numerical coincidences are chance.

The transport of cosmic rays is dominated by a variety of effects [39,40,41]:

- Ionization losses, mosty relevant for protons and nuclei. This limits the lower energy of protons to about 50 MeV *after* traversing most of the interstellar medium path, as derived from the ionizing effect [77].
- Spallation - discussed separately above. For any given isotope, spallation is a loss and a gain-process in the equation of balance.
- Radioactive decay. For any specific isotope this can be a loss and a gain-process. The resulting observed ratios provide a clock for cosmic ray transport.
- Synchrotron and Inverse Compton losses, only relevant for electrons and positrons. Above about 10 GeV these losses dominate over diffusive losses, and so the spectrum is steepened by unity. Then one deduces from the observed spectrum of $E^{-3.3}$, that injection must have happened with about $E^{-2.3}$.
- Diffusive loss from the disk. This is almost certainly governed by the spectrum of turbulence, in an isotropic approximation best described by a Kolmogorov spectrum [73]. This entails that the time scale of loss is proportional to $E^{-1/3}$. In an equilibrium situation this steepens the observed spectrum by 1/3 over the injection spectrum. Along this line of reasoning one deduces, that without re-acceleration the injection spectrum ought to be $E^{-2.35}$ approximately, as noted immediately above providing a very important consistency check.
- Convective loss from the disk. This is likely to dominate at energies below about 1 GeV for protons, or the corresponding energy of other nuclei with the same Larmor radius.
- Magnetic field irregularities; in analogy with the Sun, it is conceivable that the magnetic field is very inhomogeneous, contains flux tubes of much higher than average field, and then the transport of cosmic ray particles is governed by a mixture of streaming, convection, and diffusion by pitch angle scattering on these magnetic irregularities.
- Some cosmic rays almost certainly come from outside the Galaxy, coming down the galactic wind - of which the existence is very likely, but not certain. Using then the analogy with the solar wind, we need to again ask the question what the most likely turbulence spectrum is in the wind, and that may be quite different from a Kolmogorov spectrum [73], $k^{-5/3}$, where k is the wavenumber, and the spectrum denotes the energy per volume per wavenumber in isotropic phase space. Such a Kolmogorov spectrum is observed in the solar wind over some part of the wavenumber spectrum. Some

have argued that it could be governed by the repeated injection of supernova shockwaves, and so best be described by a k^{-2} spectrum. Interestingly, for just such a spectrum the scattering in the irregularities of cosmic ray particles becomes independent of energy, and so there would be no critical energy, below which the cosmic ray spectrum coming in from the outside is cut off. This situation would then be quite different from the solar wind, where all cosmic rays below about 500 MeV/nucleon (measured on the outside) are cut off altogether.

The transport of ultra-high energy cosmic rays, photons, and neutrinos in extragalactic space is dominated by various processes: Pion production (leading to the GZK effect) for nucleons above $\simeq 5 \times 10^{19}$ eV, electromagnetic cascades for $\gamma-$rays and, under certain circumstances, weak interactions with, for example, production and decay of Z-bosons for ultra-high energy neutrinos propagating from large redshifts. Furthermore, protons and nuclei are significantly deflected by or even diffuse in large scale extragalactic magnetic fields [78]. For a detailed discussion of these effects see the contribution by G. Sigl in this volume.

2.12 Supernovae

All stars above an original mass of more than 8 solar masses are expected to explode at the end of their life-time, after they have exhausted nuclear burning; the observable effect of such an explosion is called a supernova. When they explode, they emit about 3×10^{53} erg in neutrinos, and also about 10^{51} erg in visible energy, such as in shock waves in ordinary matter, the former stellar envelope and interstellar gas. These neutrinos have an energy in the range of a few MeV to about 20 MeV. When stars are in stellar binary systems, they can also explode at low mass, but this process is believed to give only 10 % or less of all stellar explosions. There appears to be a connection to Gamma Ray Bursts (GRBs), but the physical details are far from clear at present; some suggest a highly anisotropic explosion, others an explosion running along a pre-existing channel. It is noteworthy that above an original stellar mass of about 15 solar masses, stars also have a strong stellar wind, which for original masses above 25 solar masses becomes so strong, that it can blow out most of the original stellar mass, even before the star explodes as a supernova. The energy in this wind, integrated over the lifetime of the star, can attain the energy of the subsequent supernova, as seen in the shockwave of the explosion.

2.13 Gamma Ray Bursts

Bursts of gamma ray emission [79] come from the far reaches of the universe, and are almost certainly the result of the creation of a stellar mass black hole. The duration of these bursts ranges from a fraction of a second to usually a few seconds, and sometimes hundreds of seconds. Some such GRBs have afterglows in other wavelengths like radio, optical and X-rays, with an optical brightness which very rarely comes close to being detectable with standard binoculars. The

emission peaks near 100 keV in observable photon energy, and appears to have an underlying powerlaw character, suggesting non-thermal emission processes. See the contribution by E. Waxman in this volume for a detailed discussion.

2.14 Active Galactic Nuclei

When massive black holes accrete, then their immediate environment, usually thought to be an accretion disk and a powerful relativistic jet (i.e. where the material is ejected with a speed very close to the speed of light) emits a luminosity often far in excess of the emission of all stars in the host galaxy put together. There is the proposal of a "unified scheme", which contains the elements of a black hole, an accretion disk, a jet and a torus of surrounding molecular material. The mass range of these black holes appears to extend to 3×10^9 solar masses. As an example such black holes of a mass near 10^8 solar masses have a size of order the diameter of the Earth orbit around the Sun, and their accretion can produce a total emission of 1000 times that of all stars in our Galaxy. When the emission of the jets gets very strong, and the jet very powerful, then the radio image of such a galaxy can extend to 300 kpc, or more, dissipating the jet in radio hot spots embedded in giant radio lobes, very rarely to several Mpc. The space density of such radio galaxies, with powerful jets, hot spots and lobes, is low, less than 1/1000 of all galaxies, but on the radio sky they dominate due to their extreme emission. The activity is thought to be fed by inflow of gas and/or stars into the black hole, maybe usually fuelled by galaxy-galaxy interaction [80]. High energy particle interactions in active galactic nuclei and their surroundings may be detectable through the neutrino emission, even at cosmological distances [81]. See also the contribution by G. Pelletier in this volume.

2.15 Topological Defects and Supermassive Particles

Particle accelerator experiments and the mathematical structure of the Standard Model of the weak, electromagnetic and strong interactions suggest that these forces should be unified at energies of about $2 \times 10^{16}\,\mathrm{GeV}$ ($1\,\mathrm{GeV}= 10^9\,\mathrm{eV}$) [82], 4-5 orders of magnitude above the highest energies observed in cosmic rays. The relevant "Grand Unified Theories" (GUTs) predict the existence of X particles with mass m_X around the GUT scale of $\simeq 2 \times 10^{16}\,\mathrm{GeV}/c^2$. If their lifetime is comparable or larger than the age of the Universe, they would be dark matter candidates and their decays could contribute to cosmic ray fluxes at the highest energies today, with an anisotropy pattern that reflects the expected dark matter distribution [83]. However, in many GUTs supermassive particles are expected to have lifetimes not much longer than their inverse mass, $\sim 6.6 \times 10^{-41}(10^{16}\,\mathrm{GeV}/m_X c^2)\,\mathrm{sec}$, and thus have to be produced continuously if their decays are to give rise to ultra-high energy cosmic rays. This can only occur by emission from topological defects which are relics of cosmological phase transitions that could have occurred in the early Universe at temperatures close to the GUT scale. Phase transitions in general are associated with a breakdown of a group of symmetries down to a subgroup which is indicated by an order

parameter taking on a non-vanishing value. Topological defects occur between regions that are causally disconnected, such that the orientation of the order parameter cannot be communicated between these regions and thus will adopt different values. Examples are cosmic strings [1], magnetic monopoles [2], and domain walls [3]. The Kibble mechanism states [84] that about one defect forms per maximal volume over which the order parameter can be communicated by physical processes. The defects are topologically stable, but in the case of GUTs time dependent motion can lead to the emission of GUT scale X particles.

One of the prime cosmological motivations to postulate inflation, a phase of exponential expansion in the early Universe [85], was to dilute excessive production of "dangerous relics" such as topological defects and superheavy stable particles. However, right after inflation, when the Universe reheats, phase transitions can occur and such relics can be produced in cosmologically interesting abundances where they contribute to the dark matter, and with a mass scale roughly given by the inflationary scale. The mass scale is fixed by the CMB anisotropies to $\sim 10^{13}\,\mathrm{GeV}/c^2$ [86], and it is not far above the highest energies observed in cosmic rays, thus motivating a connection between these primordial relics and ultra-high energy cosmic rays which in turn may provide a probe of the early Universe.

Within GUTs the X particles typically decay into jets of particles whose spectra can be estimated within the Standard Model. Very roughly, one expects a few percent nucleons and the rest in neutrinos and photons [87]; these neutrinos and photons then cascade in the big bang relic neutrinos and photons, and so produce a universal photon and neutrino background (see the contribution by G. Sigl in this volume). It is not finally settled at which level we need to observe a background to confirm or refute this expected background. The resulting hadron spectrum can be a fair bit flatter than any background resulting from cosmic accelerators such as radio galaxies. Therefore any background from the decay of topological defects or other relics should produce observable signatures in neutrinos, photons and hadrons with characteristic properties. For more details on the top-down scenario see the contribution by P. Bhattacharjee and G. Sigl in this volume.

2.16 Magnetic Monopoles

The physics of electric and magnetic fields contains electric charges but no magnetic charges. In the context of particle physics it is likely that monopoles, basic magnetically charged particles, also exist. Such monopoles are a special kind of

[1] Strings correspond to the breakdown of rotational symmetry $U(1)$ around a certain direction; a laboratory example are vortices in superfluid helium.

[2] Magnetic monopoles correspond to the breakdown of arbitrary 3-dimensional rotations $SO(3)$ to rotations $U(1)$ around a specific direction.

[3] Domain walls correspond to the breakdown of a discrete symmetry where the order parameter is only allowed to take several discrete values; a laboratory example are the Bloch walls separating regions of different magnetization along the principal axis of a ferromagnet.

topological defects. The basic property of monopoles can be described as follows: a) Just as electrically charged particles shortcircuit electric fields, monopoles shortcircuit magnetic fields. The observation of very large scale and permeating magnetic fields in the cosmos shows that the universal flux of monopoles must be very low; the implied upper limit from this argument is called the *Parker limit*. b) Monopoles are accelerated in magnetic fields, just as electrically charged particles are accelerated in electric fields. In cosmic magnetic fields, the energies which can be attained are of 10^{21} eV, or even more. Any relation to the observed high energy cosmic rays is uncertain at present [88].

2.17 Primordial Black Holes and Z-bursts

In the early universe it is possible, that very small black holes were also formed. At sufficiently small mass, they can decay, and produce a characteristic spectrum of particles rather similar to topological defects [89].

Another way to obtain very energetic hadrons is to start with a neutrino at very high energy and at distances possibly much larger than the energy loss lengths $\sim 50\,\mathrm{Mpc}$ for photons, nucleons, and nuclei and have it interact with the relic neutrino background, the neutrino analogue of the CMB [90], within $\sim 50\,\mathrm{Mpc}$. Such neutrino-neutrino interactions produce a Z boson, a carrier of the electroweak interactions, which immediately decays into hadrons and other particles, thus producing a proton possibly quite near to us in the Universe. For more details on this “Z-burst” mechanism see the contributions by G. Sigl and by S. Yoshida on neutrino cascades in this volume.

3 Energies, Spectra, and Composition

The solar wind prevents low energy charged particles to come into the inner solar system, due to interaction with the magnetic field in the solar wind, a steady stream of gas going out from the Sun into all directions, originally discovered in 1950 from the effect on cometary tails: they all point outwards, at all latitudes of the Sun, and independent on whether the comet actually comes into the inner solar system, or goes outwards, in which case the tail actually precedes the head of the comet. This prevents us from knowing anything about the energies lower than about 300 MeV of interstellar energetic particles. From about 10 GeV per charge unit Z of the particle, the effect of the solar wind becomes negligible. Since cosmic ray particles are mostly fully ionized nuclei (i.e. with the exception of electrons and positrons), this is a strong effect.

Our Galaxy has a magnetic field of about 6×10^{-6} Gauss in the solar neighbourhood; the energy of such a field corresponds approximately to 1 eV per cm^3, just like the other components of the interstellar medium. In such a magnetic field charged energetic particles gyrate, with a radius of gyration, called the Larmor radius, which is proportional to the momentum of the particle perpendicular to the magnetic field direction. For highly relativistic particles this entails, that around 3×10^{18} eV protons - or other nuclei of the same energy to charge ratio

- no longer gyrate in the disk of the Galaxy, i.e. their radius of gyration is larger than the thickness of the disk. So they cannot possibly originate in the Galaxy, they must come from outside; and indeed, at that energy there is evidence for a change both in chemical composition, and in the slope of the spectrum.

The energies of these cosmic ray particles, that we observe, range from a few hundred MeV to $\simeq 300\,\mathrm{EeV}$. The integral flux ranges from about 10^{-5} per cm^2, per s, per steradian, at 1 TeV per nucleus for Hydrogen, or protons, to 1 particle per steradian per km^2 and per century around 10^{20} eV, a decrease by a factor of 3×10^{19} in integral flux, and a corresponding decrease by a factor of 3×10^{27} in differential flux, i.e. per energy interval (see also Fig. 1). Electrons have only been measured to a few TeV.

As already discussed in Sect. 2.1, the total particle spectrum is about $E^{-2.7}$ below the knee, and about $E^{-3.1}$ above the knee, at 5 PeV, and flattens again to about $E^{-2.7}$ beyond the ankle, at about 3 EeV. Electrons have a spectrum, which is similar to that of protons below about 10 GeV, and steeper, near $E^{-3.3}$ above this energy. The lower spectrum of electrons is inferred from radio emission, while the steeper spectrum at the higher energies is measured directly.

The chemical composition is rather close to that of the interstellar medium, with a few strong peculiarities relative to that of the interstellar medium, see Sect. 2.4 for a general discussion. Concerning the energy dependence towards the knee, and beyond, the fraction of heavy elements appears to continuously increase, with moderately to heavy elements almost certainly dominating beyond the knee [91], all the way to the ankle, where the composition seems to become light again [3]. This means, at that energy we observe a transition to what appears to be mostly Hydrogen and Helium nuclei. At much higher energies we can only show consistency with a continuation of these properties, we cannot prove unambiguously what the nature of these particles is.

The fraction of antiparticles is a few percent for positrons and a few 10^{-4} for anti-protons. No other anti-nuclei have been found [92].

4 Origin of Galactic Cosmic Rays

4.1 Injection

For the injection of cosmic rays the following reasons have been suggested, and we will group the answers into three segments following the very different paths of arguments.

There is first the suggestion, that low mass stars with their coronal activity provide the injection mechanism (mostly due to M. Shapiro, [93]). The main argument for this reasoning is the observation that the selection effects for the different elements among energetic particles are very similar in the solar wind and in cosmic rays. Since low mass stars are often observed to be very active, their possible contribution is expected to be substantial. In fact, in a few other stars, these selection effects have been checked [94,95].

The argument then proceeds as follows:

- Low mass stars in their coronal activity accelerate selectively certain elements to supra-thermal energies, and so inject them into the interstellar medium.
- Normal supernova explosions then accelerate them, via shock waves running through the interstellar medium.

There is second the suggestion that the injection of cosmic rays starts with ionized dust particles, and finishes by a break-up of the energetic dust. Many of the selection effects governing dust formation, and also the sites of dust formation then rule the abundances of the final cosmic ray particles.

- This model has been developed on the one hand by Luke Drury and his collaborators [96], and on the other by the group of the late Reuven Ramaty and his collaborators [46].
- One of the biggest successes of this theory is the rather good explanation for the various abundances of the chemical elements just using the known properties of dust, and the observed fact that dust is abundant everywhere.
- A challenging aspect is the possibility to explain the observational fact that the light elements such as Boron were already abundant at early times in the Galaxy, when the general abundances of all heavy elements were low; dust is formed early around the supernovae of massive stars, such as supernova 1987a, as observations clearly indicate, and so the general abundance of dust in the interstellar medium is of no significance. This aspect is one of the strengths of the approach by Ramaty. He elegantly solves the problem of the abundances of the light elements in the young Galaxy.
- The isotopic ratios of certain elements clearly suggest that at least some massive stars, such as Wolf Rayet stars, do contribute at some level. However, in this approach, they play a minor role.

There is a third, competing theory, which emphasizes the role played by the very massive stars, and their winds.

- Here the difference is noted, that massive stars come in three well-understood varieties, i) those with a zero age main sequence mass between 8 and 15 solar masses, which explode into the interstellar medium, ii) those with a mass between 15 and about 25 solar masses, which explode into their stellar wind, which is enriched mostly in Helium, and finally those with a mass above about 25 solar masses, which explode as blue supergiants, Wolf Rayet stars, for which the wind is heavily enriched in Carbon and Oxygen.
- The interstellar turbulence spectrum is taken to be of Kolmogorov type [73], as indicated by an abundance of observations and theoretical work [97].
- The injection happens from the stellar wind abundances, explaining the general features of the abundances. However, since some elements are doubly ionized, their injection is enhanced, leading to a selection effect well known from the active zones of the Sun and the solar wind, and also seen in some active stars. Therefore, this picture also uses the analogy between the solar wind, and assumes that similar selection effects play a role in the winds of massive stars.

4.2 Primary Acceleration

It has been long surmised that supernova explosions provide the bulk of the acceleration of cosmic rays in the Galaxy [98]. The acceleration is thought to be a kind of ping-pong between the two sides of the strong shock wave sent out by the explosion of the star. This ping pong is a repeated reflection via magnetic resonant interaction between the gyromotion of the energetic charged particles, and waves of the same wavelength as the Larmor motion in the magnetic thermal gas. Since the reflection is usually thought to be a gradual diffusion in direction, the process is called diffusive shock acceleration, or after its discoverer Fermi acceleration [21]; see the contribution by G. Pelletier in this volume for a detailed discussion.

For a shock wave sent out directly into the interstellar gas this kind of acceleration easily provides particle energies up to about 100 TeV. While the detailed injection mechanism is not quite clear, the very fact that we observe the emission of particles at these energies in X-rays provides a good case, and a rather direct argument for highly energetic electrons. Even though protons are by a factor of about 100 more abundant at energies near 1 GeV than electrons, we cannot prove yet directly that supernova shocks provide the acceleration; only the analogy with electrons can be demonstrated.

However, we observe what are probably Galactic cosmic rays up to energies near the knee, and beyond to the ankle, i.e. 3 EeV.

The energies can be provided by several possibilities, with the only theory worked out to a quantitative level suggesting that those particles also get accelerated in supernova shock waves, in those which run through the powerful stellar wind of the predecessor star. In this first possibility it can easily be shown, that energies up to 3 EeV per particle are possible (mostly Iron then). An alternate, second, possibility is that a ping pong between various supernova shockwaves occurs, but in this case seen from outside. In either (or any other) such theory it is a problem, that we observe a knee, i.e. a bend down of the spectrum at an energy per charge ratio which appears to be fairly sharply defined. In the concept (the first possibility) that stellar explosions are at the origin it entails that all such stars are closely similar in their properties, including their magnetic field, at the time of explosion; while this is certainly possible, we have too little information on the magnetic field of pre-supernova stars to verify or falsify this. In the case of the other concept (the second possibility) it means that the transport through the interstellar gas has a change in properties also at a fairly sharply defined energy to charge ration, indicating a special scale in the interstellar gas, for which there is no other evidence.

Galactic cosmic rays get injected from their sources with a certain spectrum. While they travel through the Galaxy, from the site of injection to escape or to the observer, they have a certain chance to leak out from the hot galactic magnetic disk of several kpc thickness. This escape becomes easier with higher energy. As a consequence their spectrum steepens, comparing source and observed spectrum. The radio observations of other galaxies show consistency with the understanding that the average spectrum of cosmic rays at least in the GeV to

many GeV energy range is always the same, in various locations in a Galaxy, and also the same in different galaxies. During this travel inside a galaxy the cosmic rays interact with the interstellar gas, and in this interaction produce gamma ray emission from pion decay, positrons, and also neutrons, anti-protons, and neutrinos. The future gamma ray emission observations will certainly provide very strong constraints on this aspect of cosmic rays.

One kind of evidence where cosmic rays exactly come from, what kind of stars and stellar explosions really dominate among their sources is the isotopic ratios of various isotopes of Neon, Iron and other heavy elements; these isotope ratios suggest that at least one population is indeed the very massive stars with strong stellar winds; however, whether these stars provide most of the heavier elements, as one theory proposes, is still quite an open question.

There is some evidence now, that just near EeV energies there is one component of galactic cosmic rays, which is spatially associated in arrival direction with the two regions of highest activity in our Galaxy, at least as seen from Earth (by AGASA and SUGAR): the Galactic Center region as well as the Cygnus region show some weak enhancement [33]. Such a directional association is only possible for neutral particles, and since neutrons at that energy can just about travel from those regions to here, before they decay (only free neutrons decay, neutrons bound into a nucleus do not decay), a production of neutrons is conceivable as one explanation of these data. One major difficulty with this interpretation is the lack of discernible high energy gamma ray emission associated with the regions of presumed neutron emission; the CASA-MIA experiment only provided stringent upper limits [99], which appear on first sight to rule out the possibility that related interactions might provide the neutrons. On the other hand, these two regions are clearly those two parts of the Galaxy, where cosmic ray interactions are the strongest, as evidenced by both lower energy gamma data as well as radio data.

4.3 Beyond the Knee

There are several ideas how to get particles accelerated to energies near and beyond the knee, at about 5×10^{15} eV. The observations of air showers suggest that the knee is a feature in constant energy per charge, or rigidity, as surmised already by B. Peters [30]. The same may be true of the "second knee", near 3×10^{17} eV.

There are again several approaches conceivable, with only one quantitative theory for this energy range:

- Obviously, a new accelerator, such as pulsars, might take over; however, then the steeper spectrum with a matching flux at the knee energy is a serious problem, and so this notion is normally discounted today.
- In the context of the injection from energetic particles from low mass active stars, an additional unidentified process provides further acceleration to those energies beyond the knee.

- In the model using dust particles as primary injection mechanism there is no account of the cosmic ray spectrum beyond the knee. A development of the theory, using acceleration between the expanding shells and shocks of different supernovae might solve this problem.
- In the theory using the supernova shock racing through stellar winds, their shell, and the immediate surroundings, all particle energies up to the ankle can be explained due to shock acceleration in the wind, which is magnetized. The knee is explained as due to a diminution of the acceleration efficiency when drift acceleration is reduced due to the matching of the Larmor radius of the motion of the particle, and the spatial constraints in a shocked shell, racing through the stellar wind.

4.4 Transport in the Galaxy

Cosmic ray particles are diffusively transported through the Galaxy, interacting all the time with the matter, magnetic fields and photons. The various theories differ in which interaction site dominates.

- In the theory using dust particles the injection is with a spectrum of $E^{-2.1}$ approximately, and so an interstellar turbulence spectrum such that it would lead to a steepening in $E^{-0.6}$ is required, for which there is little convincing observational nor theoretical evidence, except indirectly through using an adopted model of a leaky box for cosmic ray transport. Again, a further development of the theory might remedy this aspect. Especially, re-acceleration in the interstellar medium might help, as argued by Seo and Ptuskin [100].
- In the theory using stellar winds the cosmic ray interaction happens in the shells around the stellar winds [101,102], and their immediate environments, explaining readily the energy dependence of the ratio of the secondary elements from spallation and the primary elements, with $E^{-5/9}$. This also explains the gamma ray spectrum, which is observed to be best approximated by an interaction spectrum of $E^{-2.3}$. And, furthermore, this approach also explains the electron spectrum, observed to be $E^{-3.3}$, and since it is dominated by losses, requires an injection close to a spectrum of $E^{-2.3}$, as noted earlier.

For an example for detailed modeling of cosmic ray progagation and secondary production in the Galaxy see, e.g., Ref. [103].

4.5 Key Tests

In all these theories, there are critical aspects which are not yet developed, and will surely determine in the future, which of these proposals, if anyone of them, does explain what Nature is doing.

- In the picture using energetic particles from low mass active stars a key test would be the isotopic abundances, comparing those in the solar wind, and those in cosmic rays.
- In the theory using dust particle injection the expected gamma ray spectrum from cosmic ray interactions has not been worked out yet, and may finally confirm this approach, or falsify it. Also, the isotopic abundances provide key tests.
- What has yet to be done, and may well finally prove or falsify the theory involving stellar winds is the very detailed accounting of all the abundances of the chemical elements and their isotopic abundances.
- And, finally, once we observe the high energy gamma ray emission spectrum, its spatial distribution, as well as the neutrino spectrum from the inner part of our Galaxy, then we can expect to finalize our physical understanding of where cosmic rays come from.

Observations such as [104] may provide key tests for progress from the knee on up.

5 The Cosmic Rays between 3 EeV and 50 EeV

The cosmic rays between the ankle and the expected GZK-cutoff are readily explained by many possible sources, almost all outside our galaxy.

Some, but not all of these proposals can also explain particles beyond the GZK-cutoff, discussed in Sect. 6 below.

Pulsars, especially those with very high magnetic fields, called magnetars, can possibly accelerate charged particles to energies of 10^{21} eV (see contribution by B. Rudak in this volume). There are several problems with such a notion, one being the adiabatic losses on the way from close to the pulsar out to the interstellar gas, and another one the sky distribution, which should be anisotropic given the distribution and strength of Galactic magnetic fields. On the other hand if this concept could be proven, it would certainly provide a very easy explanation, why there are particles beyond the GZK-cutoff: for Galactic particles the interaction with the CMB is totally irrelevant, and no GZK-cutoff is expected.

Another proposal is GRBs, and is discussed in detail in the contribution by E. Waxman in this volume. However since ultimately we do not yet know what constitutes a GRB, their contribution cannot be settled with full certainty.

Shock waves running through a magnetized and ionized gas accelerate charged particles, as we know from in situ observations in the solar wind already; and this forms the basis of almost all theories to account for Galactic Cosmic Rays. The largest shock waves in the universe have scales of many tens of Mpc, and have shock velocities of around 1000 km/s. These shock waves arise in the cosmological large scale structure formation, seen as a soap-bubble like distribution of galaxies in the universe. The accretion flow to enhance the matter density in the resulting sheets, filaments and clusters is still continuing, and causes shock

waves to exist all around us. In the shock waves, which also have been shown to form around growing clusters of galaxies, particles can be accelerated, and can attain fairly high energies. However, the maximum energies can barely reach the energy of the GZK-cutoff, and so a strong contribution to the overall flux is unlikely [105].

The most conventional explanation is radio galaxies, which provide with their hot spots an obvious acceleration site: These hot spots are giant shock waves, often of a size exceeding that of our entire Galaxy. The shock speeds may approach several percent, maybe even several tens of percent of the speed of light, if sporadic. Integrating over all known radio galaxies readily explains flux and spectrum, as well as chemical composition of the cosmic rays in this energy range [24,106,107]. In this proposal it is the greatest challenge to identify the single radio galaxy dominating the highest energy; for this M87 has been proposed already some time ago (see also the contribution by P. Biermann et al. in this volume).

6 Particles beyond the GZK-cutoff

For these energies there is no argument, whether these particles are really protons, as an extrapolation from lower energies might suggest. However, everything we know is quite consistent with such an assumption [20].

Apart from the more "conservative" astrophysical mechanisms involving "bottom-up" acceleration, there are many exciting approaches to account for these particles:

- Decay of topological defects (TDs), or other relics from the big bang, the so-called "top-down" scenario. This theory can account readily for the apparent upturn in the spectrum beyond the GZK cutoff, and explains those events with a mixture of nucleons and $\gamma-$rays. These models predict significant diffuse $\gamma-$ray fluxes in the 100 MeV-GeV region and thus are strongly constrained by the observed fluxes in this energy range. There are many variants of top-down models [108], some of them with a quite predictive power.
- Decay of primordial black holes. The final particle distribution is rather similar to that expected from the decay of TDs [89].
- Violation of the Lorentz invariance [109]: At some very high energy, where the four basic forces of Nature combine, Lorentz Invariance may no longer hold, and a ripple effect of this is anticipated at lower energies. One possible result would be that protons might survive much longer in the bath of the CMB. In fact, observations of photons of energies up to $\simeq$ 20 TeV from Markarian 501, where absorption in the infrared background is expected to be strong, was considered as a possible signature of violation of Lorentz invariance [110,111]. Furthermore, photons at different energies would have divergent travel times, conceivably measurable with GRBs [111].

7 Outlook

The next few years promise to give great advances to our physical understanding of both the macro and the microcosmos. On the one side, this is due to our increased theoretical understanding on how to combine accelerator data and cosmic ray and astrophysical data to arrive at strong constraints, for example, on new physics. On the other hand, it is due to an expected enormous increase of data from new experiments, especially on the cosmic ray and astrophysics side. Ground arrays, Balloons, Space Station experiments will proliferate within the next few years and hold great promise for us. On a somewhat longer time scale, powerful new particle accelerators such as the LHC will directly test new physics in the TeV region, an energy range which is also, somewhat more indirectly, probed by cosmic ray, $\gamma-$ray and neutrino experiments.

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